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MEASUREMENT OF SIN 2β FROM $J/\psi\, K_S$ DECAYS

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ABSTRACT

The CP-violating parameter $\sin 2\beta$ is directly measured using 110 pb^{-1} of data accumulated with the CDF detector at the Fermilab $\overline{p}p$ Tevatron collider operating at $\sqrt{s} = 1.8$ TeV. The signal consists of 395 ± 31 $B_d^0/\overline{B}_d^0 \to J/\psi\, K_S$ events. Three tagging methods are used to identify the type of B meson at production (B_d^0 or $\overline{B}_d^0$). From the CP asymmetry, $\sin 2\beta$ is measured to be $0.79^{+0.41}_{-0.44}$, consistent with Standard Model predictions. Sin 2β is in the interval $0 < \sin 2\beta < 1$ at the 93% confidence level.

1 Introduction

Since the observation of $K_L \to \pi^+\pi^-$ in 1964 [1], the origin of CP violation has been an outstanding issue. In 1972, Kobayashi and Masakawa [2] proposed that CP violation could arise in the Standard Model through a complex phase in the quark mixing matrix (CKM matrix) if there were at least three generations of quarks. Despite precise measurements of the neutral kaon system, there has been insufficient data to fully test this idea. Recent observation of direct CP violation in kaon decays (ϵ'/ϵ) [3], improved measurements of CKM elements from B decays, and the prospect of CP-violation measurements on B hadrons give promise that this situation will change soon.

This report covers a measurement of the CP-violating parameter $\sin 2\beta$ using $B_d^0/\overline{B}_d^0 \to J/\psi K_S$ decays [4]. This is the "golden" mode for observing CP-violation in B decays, since the theoretical uncertainty in relating the measured asymmetry to the CKM elements is small and the experimental signature is clean.

The CKM matrix is a 3×3 matrix relating the weak interaction eigenstates to the mass eigenstates and can be written as

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho+i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}. \tag{1}$$

The second representation is the Wolfenstein parameterization [5], where $\lambda = \sin\theta_C$ and θ_C is the standard Cabibbo angle. A, ρ, and η are real and expected to be of order 1.

Unitary of the CKM matrix ($V^\dagger V = I$) requires that $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which is a triangle in the complex plane. Normalizing by the relatively well known product $V_{cd}V_{cb}^*$ gives the triangle shown in figure 1. The angles α, β, and γ are defined as shown in the figure. If the CP-violating phase η is nonzero, the triangle is nondegenerate, and the angles are different from both zero and π.

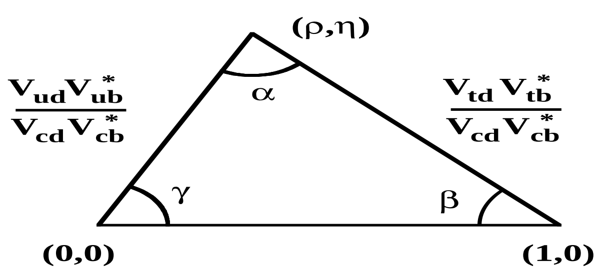

Figure 1: *The unitary triangle showing the CKM elements and defining the angles α, β, and γ.*

The final state $J/\psi\, K_S$ is a CP eigenstate. The B_d^0 may either directly decay to this state or first oscillate to a $\overline{B}_d^0$ and then decay. Since the mass eigenstates (known as B_L and B_H) are not the flavor eigenstates (B_d^0 and $\overline{B}_d^0$), an initial B_d^0 state will propagate as an oscillating mixture of B_d^0 and $\overline{B}_d^0$. The mass difference between the B_L and B_H is well known ($\Delta m_d = 0.464 \pm 0.018 ps^{-1}$), as is the average width ($\Gamma = 0.641 \pm 0.016 ps^{-1}$) [6]. The difference in widths between the B_L and B_H is expected to be small, which is assumed here.

B_d^0 mixing is governed by the box diagrams shown in figure 2, with the t quark contribution dominating. The amplitude is proportional to $V_{tb}^2 V_{td}^{*2} = |V_{tb} V_{td}|^2 e^{-2i\beta}$, giving a weak phase of -2β. The $B_d^0 \to J\psi\, K_S$ decay (figure 3) has CKM factors $V_{cb} V_{cs}^*$, which are real. Other contributions (such as penguin diagrams) are expected to be very small.

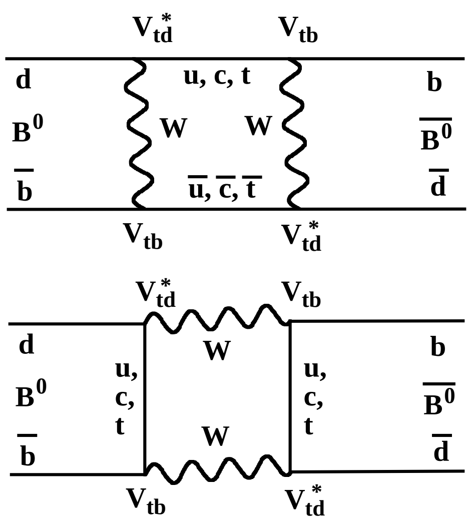

Figure 2: *Feynman box diagrams for $B_d^0/\overline{B}_d^0$ mixing showing CKM factors.*

CP violation comes from the interference of the two amplitudes – in this case one where the B_d^0 decays directly and one where it mixes first. Due to the -2β phase in the mixing, there is a $\sin 2\beta$ term in the decay rates:

$$\frac{d\Gamma(\overline{B} \to J/\psi K_S)}{dt} \propto e^{-\Gamma t}(1 + \sin 2\beta \sin \Delta m_d t) \qquad (2)$$

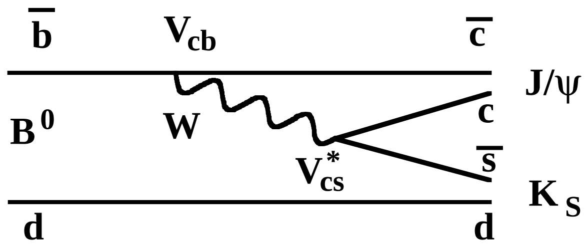

Figure 3: *Dominant Feyman diagram for the decay $B_d^0 \to J/\psi K_S$, showing the CKM factors.*

$$\frac{d\Gamma(B \to J/\psi K_S)}{dt} \propto e^{-\Gamma t}(1 - \sin 2\beta \sin \Delta m_d t). \tag{3}$$

The time-dependent, CP asymmetry is defined to be

$$A(t) \equiv \frac{\frac{d\Gamma_{\overline{B}}}{dt} - \frac{d\Gamma_B}{dt}}{\frac{d\Gamma_{\overline{B}}}{dt} + \frac{d\Gamma_B}{dt}} = \sin 2\beta \sin \Delta m_d t. \tag{4}$$

The time-averaged asymmetry is given by

$$\overline{A} \equiv \frac{\int \frac{d\Gamma_{\overline{B}}}{dt} dt - \int \frac{d\Gamma_B}{dt} dt}{\int \frac{d\Gamma_{\overline{B}}}{dt} dt + \int \frac{d\Gamma_B}{dt} dt} = \sin 2\beta \frac{\Delta m_d \Gamma}{\Delta m_d^2 + \Gamma^2}. \tag{5}$$

The factor multiplying $\sin 2\beta$ in the time-averaged asymmetry has a value of 0.47. Both the time-dependent and time-averaged asymmetries are used here.

2 Analysis Overview

The subsystems of the CDF detector [7)] primarily relevant to this measurement are (1) a silicon strip vertex detector with a secondary vertex resolution of 50–100 microns, (2) a central tracking system with momentum resoltion $(\delta P_T/P_T)^2 = (0.0066)^2 + (0.0009 P_T)$ (P_T in GeV/c), (3) central calorimeters and muon detectors.

The main elements of the analysis are (1) identification of a sample of $J/\psi\, K_S$ events, (2) tagging the flavor of the B_d at production, and (3) measurement of the proper time of the $B_d^0/\overline{B}_d^0$ decay. An unbinned maximum likelihood fit is done to extract $\sin 2\beta$.

$J/\psi\, K_S$ events are identified by the decays $J/\psi \to \mu^+\mu^-$ and $K_S \to \pi^+\pi^-$. About 400 events above background are observed.

In order to calculate a CP asymmetry, it is necessary to determine whether the $J/\psi\, K_S$ event came from a produced B_d^0 or $\overline{B}_d^0$. This is known as flavor tagging. In this measurement, three flavor tags are used – (1) same-side tagging, (2) soft lepton tagging, and (3) jet charge tagging.

Without knowing the proper time of the decay, a time-averaged asymmetry can be measured. However, knowing the proper decay time and measuring the time-dependent asymmetry improves the statistical precision on $\sin 2\beta$ by $\sim 30\%$. In CDF, the proper decay time is determined from the transverse decay length corrected for the particle's polar angle, velocity, and time dilation by the factor M_B/P_T. In this analysis, the muons from the J/ψ primarily determine the transverse decay length. In about half of the 400 $J/\psi\, K_S$ events, both muons have tracks in the CDF secondary vertex detector, allowing a precise determination of the proper time. These events are used in a time-dependent analysis. The other half of the events are used in a time-averaged analysis. The inefficiency is due to the vertex detector covering only about half of the long luminous region of the Tevatron.

3 The $B_d^0/\overline{B}_d^0 \to J/\psi K_S$ Sample

During the 1992–1996 running, a dimuon trigger provided a sample of $\sim \frac{1}{2}$ million $J/\psi \to \mu^+\mu^-$ events with the P_T of the muons above $\sim$1.5 GeV/c. The muons are required to be opposite sign and are identified by χ^2 matching in position and direction between the track in the central tracking chambers and stubs in the muon chambers outside the central calorimeters.

Since CDF has only rudimentary hadron identification, K_S reconstruction tries all oppositely charged track combinations (assumed to be pions) with invariant mass near the K_S mass. The P_T of the K_S is required to be above 0.7 GeV/c.

Events with the $J/\psi\, K_S$ P_T above 7 GeV/c are fit to secondary vertices with contraints that (1) the $\pi^+\pi^-$ mass be the K_S mass, (2) the $\pi^+\pi^-$ vertex point to the B vertex (same as the J/ψ vertex), (3) the $\mu^+\mu^-$ mass be the J/ψ mass, and (4) the B vertex point to the primary vertex. The fit is required to be of good quality, and the transverse decay length of the K_S is required to be at least five standard deviations from the J/ψ vertex. Secondary vertex

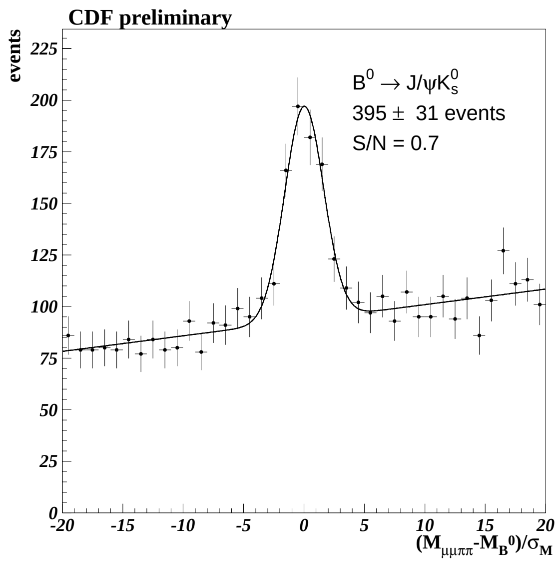

Figure 4: *Normalized mass for $J/\psi\, K_S$ candidates.*

detector information is not required for the pions but is used if avaiable.

From the momenta determined in the vertex fit and their uncertainties, the fit mass M_{fit} and its uncertainty σ_M (typically 10 to 15 MeV/c^2) are determined. The normalized mass is defined as $(M_{fit} - M_B)/\sigma_M$, where M_B is the Particle Data Group B_d^0 mass [6]. The normalized mass of the candidate events is plotted in figure 4. A fit to a Gaussian plus a linear background gives 395±31 signal events, with a signal to background ratio of roughly 1 to 2. Most of the background is at small proper times, where the CP asymmetry is small, and has reduced impact on the measurement.

4 Flavor Tagging

A measured asymmetry A_m may be reduced from the true asymmetry A due to experimental effects such as mistagging, backgrounds, and resolutions. The reduction factor is known as the dilution D ($A_m = DA$). In the case of mistagging, $D = (1-2P)$, where P is the mistag probability. The statistical power of an asymmetry measurement is ϵD^2, where ϵ is the efficiency of a tag. Thus, a sample of N events is equivalent to a sample of $\epsilon D^2 N$ perfectly tagged events.

The first tagging method used here, same-side tagging, relies on correlations of the produced B_d flavor with the charge of nearby hadrons. These correlations arise because of hadronization and decays of higher resonances. During hadronization, a $\overline{b}$ quark combines with a d quark to form a B_d^0, leaving a $\overline{d}$ quark. The $\overline{d}$ can then combine with a u quark to make a π^+. Similarly, a $\overline{B}_d^0$ is associated with a π^-. Correlated pions also arise from the decay $B^{**+} \to B_d^0 \pi^+$. This is the same correlation as from hadronization, and the two are not distinguished here. The same-side candidate tags are charged tracks within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq 0.7$ of the B, with P_T above 400 MeV/c, and with an impact parameter within 3σ of the primary vertex. If there are multiple candidates, the tag is the one with the smallest transverse momentum relative to the B [8].

Hadronization and decays from B^{**}'s are complicated processes. However, it is not necessary here to understand them in detail, because the same-side tagging efficiency and mistag probability are determined from a sample of lepton + D events. Updating the method of reference [8] to include tracks without vertex detector information, gives a dilution of $D_0 = 0.18 \pm 0.03(\mathrm{stat}) \pm 0.02(\mathrm{syst})$. The fraction of events that have a same-side tag is $65 \pm 1\%$, giving $\epsilon D^2 = 2.1 \pm 0.5\%$.

The soft lepton tag looks for electrons and muons from semileptonic decays of the B opposite to the J/ψ. Muons are identified in the same way as muons from the J/ψ and are required to have $P_T > 2$ GeV/c. Electrons are required to have a central track with $P_T > 1$ GeV/c that matches in position, energy, and shape a cluster in the central electromagnetic calorimeter. Electrons from photon conversions are eliminated. The dilution and efficiency are measured from a sample of $\sim$1000 $B^\pm \to J\psi\, K^\pm$ events, where the sign of the $B^\pm$ indicates whether a tag is correct. From the number of correctly tagged, incorrectly tagged, and untagged events, the dilution is $D = 0.625 \pm 0.146$ and the efficiency is $\epsilon = 6.5 \pm 1.0\%$, giving $\epsilon D^2 = 2.2 \pm 1.0\%$ [9].

The jet charge tag clusters tracks opposite to the $J/\psi\, K_S$ using an invariant mass algorithm with a cutoff of 5 GeV/c^2. The P_T and impact parameter weighted charge is given by

$$Q_{jet} = \frac{\sum_{tracks} q_i P_{Ti}(1 - T_i)}{\sum_{tracks} P_{Ti}(1 - T_i)}, \tag{6}$$

where T_i is the probability that track i came from the primary vertex, that is, T_i is small for B daughters. The jet charge must be between -1 and 1. If the absolute value of Q_{jet} is less than 0.2, then there is no tag. A jet charge above 0.2 (below -0.2) tags a $\overline{B}(B) \rightarrow J/\psi K_S$ event. As for the soft lepton tag, the efficiency and dilution are determined from $B^{\pm} \rightarrow J/\psi\, K^{\pm}$ decays, giving $\epsilon = 44.9 \pm 2.2\%$, $D = 0.215 \pm 0.066$, and $\epsilon D^2 = 2.2 \pm 1.3\%$ [9].

The three taggers have very different efficiencies and dilutions, but have quite similar ϵD^2's. Combining the taggers and properly taking correlations in account gives an overall ϵD^2 of $6.3 \pm 1.7\%$.

5 Results

An unbinned log-likelihood fit is done on the tagged $J/\psi\, K_S$ events. The fit has contributions from signal, prompt background, and long-lived background and includes terms for the proper lifetime, mass, and tagging dilutions. The mass difference Δm_d and lifetime Γ are fixed in the fit to the world average values. The result is

$$\sin 2\beta = 0.79^{+0.41}_{-0.44}, \tag{7}$$

where the statistical and systematic uncertainties are combined. Figure 5 shows the binned, sideband subtracted, tagging corrected asymmetry as a function of the proper decay time. The right hand point comes from the events without precise decay time information. The solid curve is the result of the fit with Δm_d fixed.

Separating the statistical and systematic uncertainties gives $\sin 2\beta = 0.79 \pm 0.39(\mathrm{stat}) \pm 0.16(\mathrm{syst})$. The systematic uncertainty is dominated by the uncertainties in the tagging dilutions and efficiencies. Other sources considered, such as, uncertainties in Δm_d, τ_{B^0}, M_B, trigger bias, and K_L regeneration, are at the 0.01 level or less.

From the likelihood function as a function of $\sin 2\beta$, the confidence level for excluding 0 (and hence establishing CP violation) can be determined. This is complicated by the result being close to a physical boundary ($\sin 2\beta = 1$). Of the several methods for handling this, the one preferred by CDF for this measurement is the one recommended by the Particle Data Group [6], namely, that of Feldman and Cousins [10]. Using this method gives $0 < \sin 2\beta < 1$ at the 93% confidence level. Using a Bayesian method with a flat prior probability

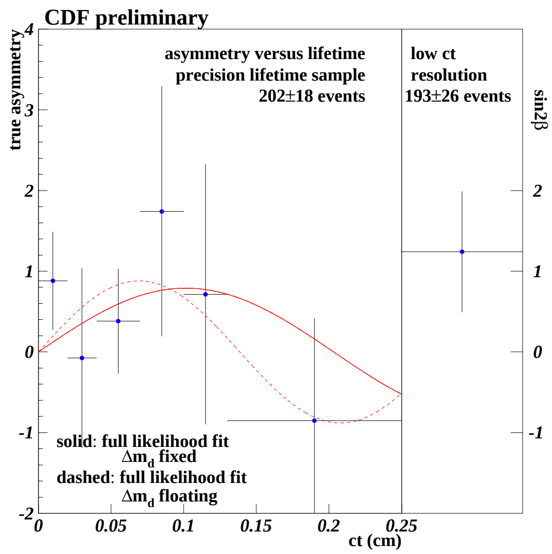

Figure 5: *Binned, sideband subtracted, tagging corrected asymmetry as a function of the proper decay time. The solide line is the result of the fit with Δm_d fixed to the world average. The right hand point is the time-averaged measurement.*

distribution gives a 95% confidence level for the same interval . If it is assumed that $\sin 2\beta = 0$, then integrating a Gaussian distribution gives a probability of observing 0.79 or greater as 3.6%.

The measured value is consistent with Standard Model fits [11)] of $0.52 \leq \sin 2\beta \leq 0.94$, at the 95% confidence level, however a precision test is not possible with the current experimental uncertainty.

6 Prospects for Run II

The upgraded Tevatron is scheduled to begin delivering data to CDF and D0 in March, 2001. The luminosity is expected to be higher, so that in two years each experiment will record 2 fb^{-1} of data, twenty times the current sample. In addition, CDF will have increased vertex detector coverage and a 25% increase in the muon and trigger efficiencies. This will yield a sample of ∼10,000 $J/\psi\, K_S$ events. Since the systematic uncertainty is dominated by uncertainties in the tagging efficiency and dilution, which are determined in the data, the uncertainty should scale as the square root of the number of events. Thus, it is expected that the uncertainty in Run II on CDF's measurement of $\sin 2\beta$ will be reduced to 0.08.

In addition, CDF is adding a $J/\psi \rightarrow e^+e^-$ trigger, further increasing the muon coverage, and improving the flavor tagging. This will reduce the uncertainty to below 0.08. Uncertainties at this level will allow strong tests of CP violation in the Standard Model.

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